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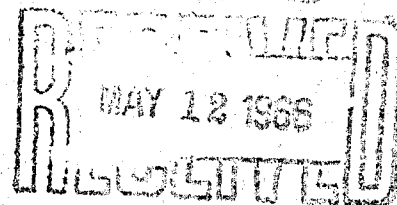
CONTINUOUS DETERMINATION OF THE AVERAGE
SOUND VELOCITY OVER AN ARBITRARY PATH

By

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(6) CONTINUOUS DETERMINATION CF THE AVERAGE SOUND

VELOCITY OVER AN ARBITRARY PATH,

(10) RICHARD D. H. LOW.

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ABSTRACT

A reasonably accurate determination of the velocity of sound in the open
air along a path of arbitrary length by some inexpensive means is the crux of
sonic atmospheric sensing. At present, this is accomplished by measuring either
time delays or phase differences of an acoustic signal. This paper explores the
technique of phase measurement and proposes a direct approach to the problem of
determining the sound speed within an arbitrary layer. By means of the phase
technique, the initial conditions of the sound velocity and the vector wind may
be determined. The temporal distribution of the sound speed is found from an
equation for the average sound velocity along the paths between the sound source
and two opposing transducers.

CONTENTS

INTRODUCTION

The fundamental problem in sonic atmospheric sensing lies in the temporal determination of an accurate speed of sound in the open air and the separation of the wind effects from the scalar thermodynamic sound speed. It is apparent that the accuracy of the latter is highly dependent upon that of the former. The usual technique (Barrett and Suomi, 1949; and John, 1960) is to measure the difference and sum of transit times of the sound pulses from a source travelling in opposite directions to two transducers, each at a specified distance from the source. At high frequencies and short distances, the difference in transit times is generally of the order of microseconds. However, the same result may be accomplished by measuring the relative phase angles (Coffman and Price, 1962), thereby magnifying the sum and difference by a factor of 2 f, where f is the frequency used. The phase technique was utilized over a long path, approximately 60 meters (Low, 1964), and was found to give satisfactory results when compared to the results derived from an array of thermocouples along the same path. Kaimal and Businger's system (1963), constructed on the same principle, measures the vertical wind and temperature variations approximately at a point by artificially presetting certain mean values of the temperature and hence of the sound velocity under windless conditions.

In the present paper, the technique of phase measurement in sonic atmospheric sensing is extended. Instead of attempting to obtain solutions for the wind components from the basic equations, an effort is made to determine continuously a reasonably accurate value of the sound velocity in the open air over an arbitrary path. Then it is a simple matter to extract both the wind and temperature data along the same path.

THEORY

Consider the isoscles triangle ABC in Figure 1 and assume that the wind vector can be resolved along the path of sound propagation, bearing in mind Schotland's (1955) excellent analysis of wind measurement by sonic means. A sound source is placed at the vertex A and a transducer at each of points B and C. In addition to those labeled in the figure, other notations are listed below:
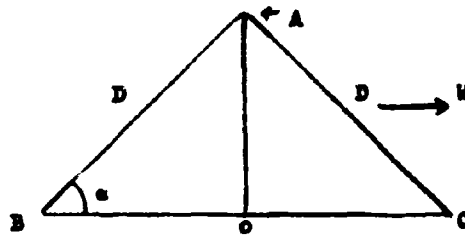

Figure 1

1

$D = AB = AC$

$C_0, C =$ the initial and subsequent velocities of sound;

$f, f' =$ the frequencies used at the sound source;

$m, n =$ the numbers of wavelengths in the paths AB and AC respectively at the given frequencies;

$t_0, t =$ the initial and subsequent transit times from A to B;

$t_0', t' =$ the initial and subsequent transit times from A to C;

$W_0, W =$ the initial and subsequent wind components;

$\lambda, \lambda' =$ the initial wavelengths along the paths AB and AC respectively;

$\Delta\phi, \Delta\phi =$ the phase differences along the paths AB and AC respectively.

    Symmetry has been assumed (see Figure 1 and notations).

    The initial conditions require that for the frequencies f and f' used, the numbers m and n must be accurately determined such that:

for path AB $D = m\lambda$ and   (1)

$$f\lambda = C_0 - W_0 \cos\alpha ; \qquad (2)$$

for path AC $D = n\lambda'$ and   (3)

$$f'\lambda' = C_0 + W_0 \cos\alpha. \qquad (4)$$

    Under these conditions, it is preferable, though not necessary, to make m and n integers.

    The travel time of a wave front emitted from the sound source A to point B, by utilizing equations (1) and (2), is given by

$$t_0 = D/(C_0 - W_0 \cos\alpha). \qquad (5)$$

    The sound velocity and the wind component are now denoted by C and W, respectively, and since they no longer represent initial conditions, a new travel time is obtained

$$t = D/(C - W \cos\alpha). \qquad (6)$$

    The difference, $\Delta t = t_0 - t$, is the time delay or time difference. From equations (5) and (6) the time difference may be determined as

$$\Delta t = \frac{D}{C_0 - W_0 \cos\alpha} - \frac{D}{C - W \cos\alpha}. \qquad (7)$$

    Solving for the velocity C by a series of algebraic manipulations, it is found that

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$$C = \frac{C_o - W_o \cos\alpha}{1 - \dfrac{(C_o - W_o \cos\alpha)\Delta t}{D}} + W \cos\alpha. \tag{8}$$

Equation (8) may be simplified by means of equations (1) and (2), noting that $f/m = (C_o - W_o \cos\alpha)/D$.

$$C = \frac{C_o - W_o \cos\alpha}{1 - f\Delta t/m} + W \cos\alpha. \tag{9}$$

The difference in time Δt can now be expressed as the difference in phase angle $\Delta\phi$ by the formula $\Delta\phi = 2\Pi f \Delta t$. Substitution of this formula into equation (9) gives the desired expression for the average sound velocity C in terms of phase difference with respect to the initial conditions

$$C = \frac{C_o - W_o \cos\alpha}{1 - \Delta\phi'/2m\,\Pi} + W \cos\alpha. \tag{10}$$

By the same series of manipulations, using $\Delta t' = t_o' - t'$ for the path AC, the following expression for the average sound velocity along AC is found to be:

$$C = \frac{C_o + W_o \cos\alpha}{1 - \Delta\phi'/2n\Pi} - W \cos\alpha. \tag{11}$$

Expressions (10) and (11) form a pair of simultaneous equations and can be solved exactly, if so desired; however, the result may not sufficiently justify the effort. Solving for the average sound velocity C by combining the above two equations, we obtain

$$2C = (C_o - W_o \cos\alpha)/(1 - \Delta\phi/2m\Pi)$$
$$+ (C_o + W_o \cos\alpha)/(1 - \Delta\phi'/2n\Pi). \tag{12}$$

Generally, $\Delta\phi$, $\Delta\phi' \ll 2m\pi$, $2n\pi$ respectively; it is reasonable to take the following approximations:

$$1/(1 - \Delta\phi/2m\Pi) \doteq 1 + \Delta\phi/2m\Pi, \text{ and}$$
$$1/(1 - \Delta\phi'/2n\Pi) \doteq 1 + \Delta\phi'/2n\Pi. \tag{13}$$

Upon ansion of equation (12) using the above approximations and factoring, we o. .in two terms

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$$-(\Delta\phi/2m\pi) \; W_o \; \cos\alpha/C_o \quad \text{and} \quad + \; (\Delta\phi'/2n\pi) \; W_o \; \cos\alpha/C_o$$

$$(14)$$

which are not much different from zero. Thus, a reasonably accurate expression
for the continuous average sound velocity along an arbitrary path is given by

$$C \doteq C_o \left[1 + \frac{1}{4\pi} \; (\Delta\phi/m + \Delta\phi'/n)\right].$$

$$(15)$$

The average acoustic virtual temperature (Suomi, 1949) in degrees absolute
along the path, which will not be appreciably different from the average free
air temperature along the same path with low humidity conditions, is readily
obtainable from the average sound velocity C given above by means of the Laplace
formula.

To obtain the average horizontal wind component across the paths, equations
(10) and (11) are solved simultaneously and, with approximations, yield

$$2W \cos\alpha \doteq 2 \, W_c \; \cos\alpha \; -(C_o - W_o \; \cos\alpha) \; \Delta\phi/2m\pi$$

$$+ \; (C_o + W_o \; \cos\alpha)\Delta\phi'/2n\pi.$$

$$(16)$$

Equations (1), (2), (3), and (4), the initial conditions, and the fact that
$\cos\alpha = d/D$ are used to simplify this expression. The average horizontal wind
component W is then given by

$$W \doteq W_o \; - \; \frac{1}{4\pi d} \; (f\lambda^2 \Delta\phi - f'\lambda'^2 \Delta\phi').$$

$$(17)$$

DISCUSSION AND CONCLUSIONS

The initial conditions may conceivably cause some concern as to their mean-
ing. Actually, the setting of the initial conditions could be termed calibra-
tion which is a required step for any instrument. Under normal weather condi-
tions, this setting need not be at all altered if there is no drift in the elec-
tronic equipment.

In the course of developing the equations in the preceding section, no re-
strictions have been imposed thereon, except for approximations which are con-
sidered reasonable and should in no manner jeopardize the precision of measure-
ment within the limitations of the electronic equipment. Equations (15) and
(17) are generalized forms; however, the frequencies chosen do not have to be
different, in which case either m or n may take on the value of a noninteger.
The use of a single frequency does not greatly simplify the computations, but it
has the advantage of presenting a visual picture of the wind effect when the
temperature remains unchanged during a short interval of observation, and it may
bring about some economy in instrumentation. Furthermore, as may be obvious
from equations (2) and (4), the wind effect will cause the phase angles $\Delta\phi$ and
$\Delta\phi'$ to assume opposite signs, thereby indicating the sense of the wind direc-
tion, while the temperature effect will cause them to have the same sign, either
negative or positive, depending on the initial calibration values.

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The system is highly sensitive to wind and temperature changes; therefore, the frequency or frequencies to be used should be selected with care. Unless a higher resolution is required, the lower audible frequencies should be used for reasons noted below. As shown before, $\Delta\Phi = 2 f \Pi t$. Normally a change of $1^\circ C$ in temperature will cause a change of about 0.6 meter per second in sound speed. Now assume that the time difference Δt, as a result of a change of $1^\circ C$, is about 1 millisecond. It is easily seen that at $f = 100$ cps, $\Delta\Phi = 0.36^\circ$; at $f = 1000$ cps, $\Delta\Phi = 3.6^\circ$, etc. The same reasoning holds for a change in the wind field. Moreover, the longer the path D, the larger the time difference Δt and the greater the desirability to use lower frequencies.

As the angle α in Figure 1 becomes larger and larger, the value of $W \cos\alpha$ approaches the vertical component of the vector wind. As the angle α approaches 90 degrees, the system will have become a device for temperature measurement, the vertical components being negligible under normal conditions. The average free air temperature in degrees absolute along the path may then be obtained directly from the observed phase angle

$$T = T_0 \left(1 + 0.00556 \, \Delta\phi/m\right).$$

(18)

At the other extreme, as the value of $\cos\alpha$ approaches one, the system assumes the familiar geometry employed in sonic anemometry-thermometry. As the distance between the transducers and sound source is reduced, approximate point measurement is attained.

It may be recalled that in the text the word "wind component" has been employed to emphasize the fact that the wind so obtained is not the total wind vector but a component thereof, depending on the orientation of the system. If two more transducers are available so that each is oriented orthogonally to the next, it is then possible to obtain the average total wind field across the array.

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REFERENCES

Barrett, E., and V. E. Suomi, "Preliminary Report on Temperature Measurement by Sonic Means," *J. Meteorol.*, June 1949, pp. 273-276.

Coffman, J. W., and R. G. Price, "Some Errors Associated with Acoustical Wind Measurements through a Layer," U. S. Army Electronics R & D Activity, White Sands Missile Range, New Mexico, Tech. Report SELWS-MM-12, October 1962, 11 pp.

John, R. S., "Field Tests of a Sonic Anemometer-Thermometer," *Bull. Amer. Meteorol. Soc.*, November 1960, pp. 618-626.

Kaimal, J. C., and J. A. Businger, "A Continuous Wave Sonic Anemometer-Thermometer," *J. Meteorol.*, February 1963, pp. 156-164.

Low, R. D. H., "Acoustic Measurements of Wind through a Layer," U. S. Army Electronics R & D Activity, White Sands Missile Range, New Mexico, Tech. Report ERDA-125, March 1964, 47 pp.

Schotland, R. M., "Measurement of Wind Velocity by Sonic Means," J. Meteorol., December 1955, pp. 386-390.

ATMOSPHERIC SCIENCES RESEARCH PAPERS

1. Webb, W.L., "Development of Droplet Size Distributions in the Atmosphere," June 1954.

2. Hansen, F. V., and H. Rachele, "Wind Structure Analysis and Forecasting Methods for Rockets," June 1954.

3. Webb, W. L., "Net Electrification of Water Droplets at the Earth's Surface," *J. Meteorol.*, December 1954.

4. Mitchell, R., "The Determination of Non-Ballistic Projectile Trajectories," March 1955.

5. Webb, W. L., and A. McPike, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #1, March 1955.

6. Mitchell, R., and W. L. Webb, "Electromagnetic Radiation through the Atmosphere," #1, April 1955.

7. Webb, W. L., A. McPike, and H. Thompson, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #2, July 1955.

8. Barichivich, A., "Meteorological Effects on the Refractive Index and Curvature of Microwaves in the Atmosphere," August 1955.

9. Webb, W. L., A. McPike and H. Thompson, "Sound Ranging Technique for Determining the Trajectory of Supersonic Missiles," #3, September 1955.

10. Mitchell, R., "Notes on the Theory of Longitudinal Wave Motion in the Atmosphere," February 1956.

11. Webb, W. L., "Particulate Counts in Natural Clouds," *J. Meteorol.*, April 1956.

12. Webb, W. L., "Wind Effect on the Aerobee," #1, May 1956.

13. Rachele, H., and L. Anderson, "Wind Effect on the Aerobee," #2, August 1956.

14. Beyers, N., "Electromagnetic Radiation through the Atmosphere," #2, January 1957.

15. Hansen, F. V., "Wind Effect on the Aerobee," #3, January 1957.

16. Kershner, J., and H. Bear, "Wind Effect on the Aerobee," #4, January 1957.

17. Hoidale, G., "Electromagnetic Radiation through the Atmosphere," #3, February 1957.

18. Querfeld, C. W., "The Index of Refraction of the Atmosphere for 2.2 Micron Radiation," March 1957.

19. White, Lloyd, "Wind Effect on the Aerobee," #5, March 1957.

20. Kershner, J. G., "Development of a Method for Forecasting Component Ballistic Wind," August 1957.

21. Layton, Ivan, "Atmospheric Particle Size Distribution," December 1957.

22. Rachele, Henry and W. H. Hatch, "Wind Effect on the Aerobee," #6, February 1958.

23. Beyers, N. J., "Electromagnetic Radiation through the Atmosphere," #4, March 1958.

24. Prosser, Shirley J., "Electromagnetic Radiation through the Atmosphere," #5, April 1958.

25. Hoidale, G., "Electromagnetic Propagation through the Atmosphere," #6, February 1959.

26. McLardie, M., R. Helvey, and L. Traylor, "Low-Level Wind Profile Prediction Techniques," #1, June 1959.

27. Lamberth, Roy, "Gustiness at White Sands Missile Range," #1, May 1959.

28. Beyers, N. J., B. Hinds, and G. Hoidale, "Electromagnetic Propagation through the Atmosphere," #7, June 1959.

29. Hainline, D. A., "Drag Cord-Aerovane Equation Analysis for Computer Application," August 1959.

30. Hoidale, G. B., "Slope-Valley Wind at WSMR," October 1959.

31. Webb, W. L., and K. R. Jenkins, "High Altitude Wind Measurements," *J. Meteorol.*, 16, 5, October 1959.

32. White, Lloyd, "Wind Effect on the Aerobee," #9, October 1959.

33. Webb, W. L., J. W. Coffman, and G. Q. Clark, "A High Altitude Acoustic Sensing System," December 1959.

34. Webb, W. L., and K. R. Jenkins, "Application of Meteorological Rocket Systems," J. Geophys. Res., 64, 11, November 1959.

35. Duncan, Louis, "Wind Effect on the Aerobee," #10, February 1960.

36. Helvey, R. A., "Low-Level Wind Profile Prediction Techniques," #2, February 1960.

37. Webb, W. L., and K. R. Jenkins, "Rocket Sounding of High-Altitude Parameters," *Proc. GM Rel. Symp.*, Dept. of Defense, February 1960.

38. Webb, W. L., and K. R. Jenkins, "Speed of Sound in the Stratosphere," Jun 960.

39. Webb, W. L., K. R. Jenkins, and G. Q. Clark, "Rocket Sounding of High Atmosphere Meteorological Parameters," *IRE Trans. Mil. Elect.*, MIL-4, 2-3, April-July 1960.

10

40. Helvey, R. A., "Low-Level Wind Profile Prediction Techniques," #3, September 1960.

41. Beyers, N. J., and O. W. Thiele, "Meteorological Wind Sensors," August 1960.

42. Armijo, Larry, "Determination of Trajectories Using Range Data from Three Non-colinear Radar Stations," September 1960.

43. Carnes, Patsy Sue, "Temperature Variations in the First 200 Feet of the Atmosphere in an Arid Region," July 1961.

44. Springer, H. S., and R. O. Olsen, "Launch Noise Distribution of Nike-Zeus Missiles," July 1961.

45. Thiele, O. W., "Density and Pressure Profiles Derived from Meteorological Rocket Measurements," September 1961.

46. Diamond, M. and A. B. Gray, "Accuracy of Missile Sound Ranging," November 1961.

47. Lamberth, R. L. and D. R. Veith, "Variability of Surface Wind in Short Distances," #1, October 1961.

48. Swanson, R. N., "Low-Level Wind Measurements for Ballistic Missile Application," January 1962.

49. Lamberth, R. L. and J. H. Grace, "Gustiness at White Sands Missile Range," #2, January 1962.

50. Swanson, R. N. and M. M. Hoidale, "Low-Level Wind Profile Prediction Techniques," #4, January 1962.

51. Rachele, Henry, "Surface Wind Model for Unguided Rockets Using Spectrum and Cross Sprectrum Techniques," January 1962.

52. Rachele, Henry, "Sound Propagation through a Windy Atmosphere," #2, February 1962.

53. Webb, W. L., and K. R. Jenkins, "Sonic Structure of the Mesosphere," *J. Acous. Soc. Amer.*, 34, 2, February 1962.

54. Tourin, M. H. and M. M. Hoidale, "Low-Level Turbulence Characteristics at White Sands Missile Range," April 1962.

55. Miers, Bruce T., "Mesospheric Wind Reversal over White Sands Missile Range," March 1962.

56. Fisher, E., R. Lee, and H. Rachele, "Meteorological Effects on an Acoustic Wave within a Sound Ranging Array," May 1962.

57. Walter, E. L., "Six Variable Ballistic Model for a Rocket," June 1962.

58. Webb, W. L., "Detailed Acoustic Structure Above the Tropopause," *J. Applied Meteorol.*, 1, 2, June 1962.

59. Lamberth, Roy, "Wind Variability Estimates as a Function of Sampling Interval," July 1962.

60. Rachele, Henry, "Surface Wind Sampling Periods for Unguided Rocket Impact Prediction," July 1962.

61. Traylor, Larry, "Coriolis Effects on the Aerobee-Hi Sounding Rocket," August 1962.

62. McCoy, J., and G. Q. Clark, "Meteorological Rocket Thermometry," August 1962.

63. Rachele, Henry, "Real-Time Prelaunch Impact Prediction System," August 1962.

64. Beyers, Norman, and Norman Wagner, "Performance Characteristics of Meteorological Rocket Wind and Temperature Sensors," October 1962.

65. Coffman, J., and R. Price, "Some Errors Associated with Acoustical Wind Measurements through a Layer," October 1962.

36. Armendariz, M., E. Fisher, and J. Serna, "Wind Shear in the Jet Stream at WSMR," November 1962.

67. Armendariz, M., F. Hansen, and S. Carnes, "Wind Variability and its Effect on Rocket Impact Prediction," January 1963.

68. Querfeld, C., and Wayne Yunker, "Pure Rotational Spectrum of Water Vapor, I: Table of Line Parameters," February 1963.

69. Webb, W. L., "Acoustic Component of Turbulence," *J. Applied Meteorol.*, 2, 2, April 1963.

70. Beyers, N. and L. Engberg, "Seasonal Variability in the Upper Atmosphere," May 1963.

71. Lamberth, Roy and D. Veith, "Upper Wind Correlations in Southwestern United States," June 1963.

72. Sandlin, E., "An Analysis of Wind Shear Differences as Measured by AN/FPS-16 Radar and AN/GMD-1B Rawinsonde," August 1963.

73. Diamond, M. and R. P. Lee, "Statistical Data on Atmospheric Design Properties Above 30 km," August 1963.

74. Thiele, O. W., "Mesospheric Density Variability Based on Recent Meteorological Rocket Measurements," *J. Applied Meteorol.*, 2, 5, October 1963.

75. Diamond, M., and O. Essenwanger, "Statistical Data on Atmospheric Design Properties to 30 km," *Astro. Aero. Engr.*, December 1963.

76. Hansen, F. V., "Turbulence Characteristics of the First 62 Meters of the Atmosphere," December 1963.

77. Morris, J. E., and B. T. Miers, "Circulation Disturbances Between 25 and 70 kilometers Associated with the Sudden Warming of 1963," *J. of Geophys. Res.*, January 1964.

78. Thiele, O. W., "Some Observed Short Term and Diurnal Variations of Stratospheric Density Above 30 km," January 1964.

79. Sandlin, R. E., Jr. and E. Armijo, "An Analysis of AN/FPS-16 Radar and AN/GMD-1B Rawinsonde Data Differences," January 1964.

80. Miers, B. T., and N. J. Beyers, "Rocketsonde Wind and Temperature Measurements Between 30 and 70 km for Selected Stations," *J. Applied Meteorol.*, February 1964.

81. Webb, W. L., "The Dynamic Stratosphere," *Astronautics and Aerospace Engineering*, March 1964.

82. Low, R. D. H., "Acoustic Measurements of Wind through a Layer," March 1964.

83. Diamond, M., "Cross Wind Effect on Sound Propagation," *J. Applied Meteorol.*, April 1964.

84. Lee, R. P., "Acoustic Ray Tracing," April 1964.

85. Reynolds, R. D., "Investigation of the Effect of Lapse Rate on Balloon Ascent Rate," May 1964.

86. Webb, W. L., "Scale of Stratospheric Detail Structure," *Space Research V*, May 1964.

87. Barber, T. L., "Proposed X-Ray-Infrared Method for Identification of Atmospheric Mineral Dust," June 1964.

88. Horn, J. D., and E. J. Trawle, "Orographic Effects on Wind Variability," July 1964.

89. Hoidale, G., C. Querfeld, T. Hall, and R. Mireles, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #1, September 1964.

90. Duncan, L. D., R. Ensey, and B. Engebos, "Athena Launch Angle Determination," September 1964.

91. Duncan, L. D., and R. Ensey, "Six-Degree-of-Freedom Digital Simulation Model for Unguided, Fin-Stabilized Rockets," November 1964.

92. Hoidale, G., C. Querfeld, T. Hall, and R. Mireles, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #2, November 1964.

93. Webb, W. L., "Stratospheric Solar Response," *J. Atmos. Sci.*, November 1964.

94. McCoy, J. and G. Clark, "Rocketsonde Measurement of Stratospheric Temperature," December 1964.

95. Farone, W. A., "Electromagnetic Scattering from Radially Inhomogeneous Spheres as Applied to the Problem of Clear Atmosphere Radar Echoes," December 1964.

13

96. Farone, W. A., "The Effect of the Solid Angle of Illumination or Observation on the Color Spectra of 'White Light' Scattered by Cylinders," January 1965.

97. Williamson, L. E., "Seasonal and Regional Characteristics of Acoustic Atmospheres," *J. Geophys. Res.*, January 1965.

98. Armendariz, M., "Ballistic Wind Variability at Green River, Utah," January 1965.

99. Low, R. D. H., "Sound Speed Variability Due to Atmospheric Composition," January 1965.

100. Querfeld, C. W., "Mie Atmospheric Optics," *J. Opt. Soc. Amer.*, January 1965.

101. Coffman, J., "A Measurement of the Effect of Atmospheric Turbulence on the Coherent Properties of a Sound Wave," January 1965.

102. Rachele, H., and D. Veith, "Surface Wind Sampling for Unguided Rocket Impact Prediction," January 1965.

103. Ballard, H., and M. Izquierdo, "Reduction of Microphone Wind Noise by the Generation of a Proper Turbulent Flow," February 1965.

104. Mireles, R., "An Algorithm for Computing Half Widths of Overlapping Lines on Experimental Spectra," February 1965.

105. Richart, H., "Inaccuracies of the Single-Theodolite Wind Measuring System in Ballistic Application," February 1965.

106. D'Arcy, M., "Theoretical and Practical Study of Aerobee-150 Ballistics," March 1965.

107. McCoy, J., "Improved Method for the Reduction of Rocketsonde Temperature Data," March 1965.

108. Mireles, R., "Uniqueness Theorem in Inverse Electromagnetic Cylindrical Scattering," April 1965.

109. Coffman, J., "The Focusing of Sound Propagating Vertically in a Horizontally Stratified Medium," April 1965.

110. Farone, W. A., and C. Querfeld, "Electromagnetic Scattering from an Infinite Circular Cylinder at Oblique Incidence," April 1965.

111. Rachele, H., "Sound Propagation through a Windy Atmosphere," April 1965.

112. Miers, B., "Upper Stratospheric Circulation over Ascension Island," April 1965.

113. Rider, L., and M. Armendariz, "A Comparison of Pibal and Tower Wind Measurements," April 1965.

114. Hoidale, G. B., "Meteorological Conditions Allowing a Rare Observation of 24 Micron Solar Radiation Near Sea Level," *Meteorol. Magazine*, May 1965.

115. Beyers, N. J., and B. T. Miers, "Diurnal Temperature Change in the Atmosphere Between 30 and 60 km over White Sands Missile Range," *J. Atmos. Sci.*, May 1965.

14

116. Querfeld, C., and W. A. Farone, "Tables of the Mie Forward Lobe," May 1965.

117. Farone, W. A., "Generalization of Rayleigh-Gans Scattering from Radially Inhomogeneous Spheres," *J. Opt. Soc. Amer.*, June 1965.

118. Diamond, M., "Note on Mesospheric Winds Above White Sands Missile Range," *J. Applied Meteorol.*, June 1965.

119. Clark, G. Q., and J. G. McCoy, "Measurement of Stratospheric Temperature," *J. Applied Meteorol.*, June 1965.

120. Hall, T., G. Hoidale, R. Mireles, and C. Querfeld, "Spectral Transmissivity of the Earth's Atmosphere in the 250 to 500 Wave Number Interval," #3, July 1965.

121. McCoy, J., and C. Tate, "The Delta-T Meteorolobical Rocket Payload," June 1965.

122. Horn, J. D., "Obstacle Influence in a Wind Tunnel," July 1965.

123. McCoy, J., "An AC Probe for the Measurement of Electron Density and Collision Frequency in the Lower Ionosphere," July 1965.

124. Serna, J., "An Acoustic Ray Tracing Method for Digital Computation," September 1965.

125. Webb, W. L., "Morphology of Noctilucent Clouds," *J. Geophys. Res.*, 70, 18, 4463-4475, September 1965.

126. Kays, M., and R. A. Craig, "On the Order of Magnitude of Large-Scale Vertical Motions in the Upper Stratosphere," *J. Geophys. Res.*, 70, 18, 4453-4462, September 1965.

127. Lamberth, R. L., R. Reynolds, and Morton Wurtele, "The Mountain Lee Wave at White Sands Missile Range," *Bull. Amer. Meteorol. Soc.*, 46, 10, October 1965.

128. Reynolds, R. and R. L. Lamberth, "Ambient Temperature Measurements from Radiosondes Flown on Constant-Level Balloons," October 1965.

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132. Diamond, M., and R. P. Lee, "Long-Range Atmospheric Sound Propagation," *J. Geophys. Res.*, 70, 22, November 1965.

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134. Hansen, F. V., and P. S. Hansen, "Formation of an Internal Boundary over Heterogeneous Terrain," November 1965.

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135. Webb, W. L., "Mechanics of Stratospheric Seasonal Reversals," November 1965.

136. U. S. Army Electronics R & D Activity, "U. S. Army Participation in the Meteorological Rocket Network," January 1966.

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138. Webb, W. L., "Diurnal Variations in the Stratospheric Circulation," February 1966.

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13. ABSTRACT

A reasonably accurate determination of the velocity of sound in the open air along a path of arbitrary length by some inexpensive means is the crux of sonic atmospheric sensing. At present, this is accomplished by measuring either time delays or phase differences of an acoustic signal. This paper explores the technique of phase measurement and proposes a direct approach to the problem of determining the sound speed within an arbitrary layer. By means of the phase technique, the initial conditions of the sound velocity and the vector wind may be determined. The temporal distribution of the sound speed is found from an equation for the average sound velocity along the paths between the sound source and two opposing transducers.

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